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# Absorption and fluorescence phenomena of optical fibers under heavy neutron irradiation

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**Abstract**

For applying to optical diagnostics for fusion reactor, two types of radiation-resistant optical fibers have been fabricated and their optical phenomena were examined in the JMTR. The optical absorption due to radiation-induced defects and formation of color centers, is concentrated in the wavelengths less than 700 nm. By contrast, the absorption was quite low in the wavelength range from 700 to 1500 nm. The optical fibers appeared to have good radiation resistance and survived neutron irradiation up to $2 \times 10^{24}$ n/m$^2$. During JMTR irradiation, strong optical emission from 400 to 1400 nm with a sharp peak intensity at 1270 nm was observed. The peak value at 1270 nm is directly proportional to the reactor power. The results of absorption and fluorescence phenomena suggest the possibility of multi-parameter sensing for fusion reactor diagnostics. 

## 1. Introduction

Many intensive studies have been conducted for the effects of radiation on optical fibers [1–3]. In these studies, two significant optical effects were pointed out for practical application in a heavy radiation environment. One is the increase in signal transmission-loss due to the radiation induced defects and the formation of color centers. Other is the optical emission in the optical fibers through the process of fluorescence phenomena under high dose rates of radiation.

For application to optical diagnostics for fusion reactors, these radiation related phenomena should be examined by heavy irradiation experiments. Owing to this, two types of radiation-resistant optical fibers have been fabricated and heavy neutron irradiation tests were carried out in the JMTR fission reactor. The radiation-resistant optical fibers, pure-silica ($SiO_2$) core and Fluorine (F)-doped core optical fiber, were irradiated and their dynamic optical phenomena were examined during heavy neutron irradiation.

This paper discusses the dynamic optical phenomena during heavy neutron irradiation and the possibility of multi-parameter sensing for fusion reactor diagnostics using radiation-resistant optical fibers.

## 2. Radiation resistant optical fibers and experimental details

The radiation-resistance of optical fibers is dependent on the glass structure which is determined by the changing of the refractive index of core and cladding with the dopants. In the previous investigations for the development of radiation-resistant optical fibers, it was found that the pure-$SiO_2$ core optical fiber has better radiation-resistance compared with $GeO_2$ and/or $P_2O_5$ doped $SiO_2$ core optical fibers [1–3]. The structure of pure-$SiO_2$ glass, which consists of common stable bonding, is much more simple than that of multi-component glass. Further findings suggest that the Fluorine (F) content of the $SiO_2$ core also improves the radiation-

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Table 1
Radiation-resistant optical fibers used for experiments

| No. of sample | Types of fiber | Core | | Cladding | |
|---|---|---|---|---|---|
| | | Composition | Diameter (μm) | Composition | Diameter (μm) |
| 1 | Step index pure-silica | $SiO_2$ | 200 | $SiO_2$–F F:4.0 wt% | 250 |
| 2 | Step index F-dope | $SiO_2$–F F:1.6 wt% | 200 | $SiO_2$–F F:5.6 wt% | 250 |

resistivity of optical fibers. The effect of F-content blocks the formation of E′ center and NBOHC (non-bridging oxygen hole center) in the $SiO_2$ glass and also adding to the $SiO_2$ core improves its radiation-resistance [4,5].

The radiation-resistant optical fibers used here are shown in Table 1. Two types of $SiO_2$ based core optical fibers, fiber No. 1 of pure-$SiO_2$ core and fiber No. 2 of pure-$SiO_2$ with F-doped core were used for experiments. Both types of optical fibers consist of F-doped $SiO_2$ cladding and 300 μm outer diameter aluminum-jacket. The contents of fluorine in the core and in the cladding of fiber No. 2 were, 1.6 wt% and 5.6 wt%, respectively.

Experiments were carried out in the JMTR fission reactor at JAERI. A special capsule in the core region of the reactor was used to irradiate the optical fibers. The irradiated length of the optical fibers was about 1 m. The optical fibers were irradiated up to a fast neutron ($E > 1$ MeV) fluence of $2 \times 10^{24}$ n/m$^2$ at fluxes of $4 \times 10^{17}$ n/m$^2$ s, with a gamma-ray dose of $5 \times 10^9$ Gy. Fig. 1 shows the measuring procedure for experiments. The radiation-induced optical absorption and optical emission in the optical fibers were measured with an optical spectrum analyzer (Ando AQ-6315A) in the wavelength range of 350–1800 nm. The AQ-6315A optical spectrum analyzer is measuring the optical power density and its sensitivity is about −80 dB m ($10^{-11}$ W). One end of the optical fiber was connected to a Xenon-lamp white-light-source (Ando AQ-4303B) and the other end to the optical spectrum analyzer.

## 3. Results and discussion

### 3.1. Radition induced absorption

One serious problem for optical fibers is the increase in signal transmission-loss due to radiation-induced defects and the formation of color centers. It is known that radiation with high energy particles causes ionization and atomic displacements within the molecular bonding network of $SiO_2$ glass.

An example of the observed optical transmission spectra of the $SiO_2$ based optical fibers by fission neutron irradiation is shown in Fig. 2. The figure shows the induced optical absorption of F-doped core optical fiber and pure-$SiO_2$ core optical fiber. As a result of neutron irradiation, the following characteristics have become clear. The absorption induced by heavy neutrons is concentrated in the UV to visible wavelength region. The optical absorption in the UV to visible wavelenth was previously reported [5,6]. Large and permanent

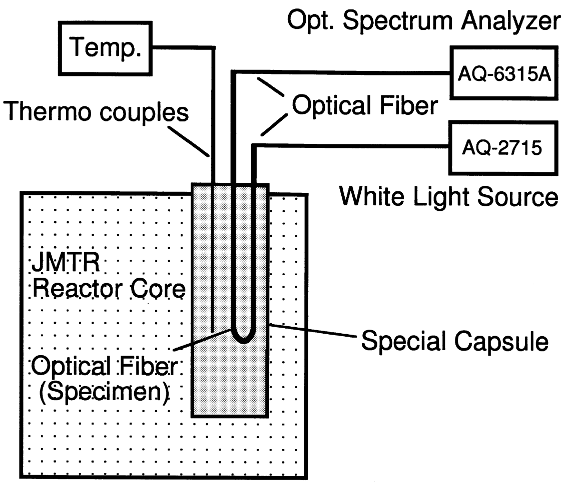


Fig. 1. Measuring procedure for absorption and fluorescence phenomena of optical fibers.

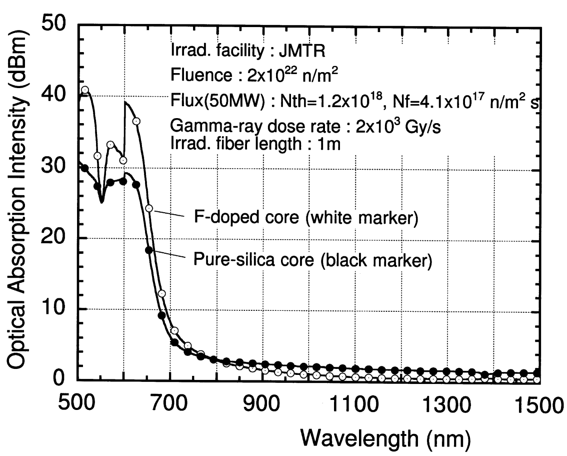


Fig. 2. Observed optical absorption spectra of F-doped core fiber and pure-silica core fiber by fission neutron irradiation.

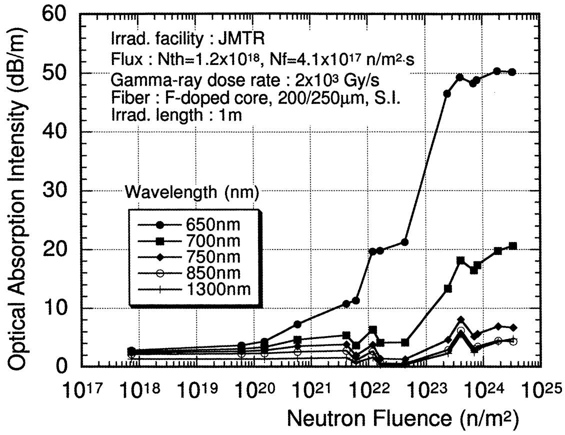


Fig. 3. Increase in monochromatic optical absorption of F-doped core fiber during fission neutron irradiation.

absorption losses at wavelengths of less than 700 nm due to E′ center and NBOHC was observed. By contrast, the increase in absorption of both radiation-resistant optical fibers were quite low in the wavelength range from 700 to 1500 nm. Fig. 3 shows the increase in monochromatic optical transmission for the F-doped core optical fiber during irradiation. The increase in transmission-loss at the end of irradiation period was a few dB/m in the wavelength range from 750 to 1500 nm. Both types of radiation-resistant optical fibers survived fast neutron irradiation up to about $2 \times 10^{24}$ n/m$^2$, concurrent with gamma-ray doses of $5 \times 10^9$ Gy. In the case of heavy neutron irradiation, the absorption of F-doped core optical fiber is quite similar to that of pure-$SiO_2$ core fiber.

In the previous investigation of medium-dose gamma-ray irradiation, the absorption of F-doped core fiber was quite low as compared with pure-$SiO_2$ core fiber [5]. An example of the absorption spectra by the gamma-ray irradiation is shown in Fig. 4. Furthermore, large and comparatively rapid recovery of absorption was observed after irradiation.

One of the main reasons for the permanent absorption by the heavy neutron irradiation is the influence of atomic displacement. The rapid recovery of the optical absorption for gamma-ray irradiation is related to the ionization. The result of absorption measurements show that effects of the irradiation associated with heavy neutron is different from the effects of ionizing irradiation.

### 3.2. Radiation induced fluorescence

Another significant effect, namely the optical emission in the fibers through a fluorescence process was observed [7–9]. An example of the spectral optical emission in the F-doped core fiber and pure-$SiO_2$ core fiber is shown in Fig. 5. The optical emission, which ranged from 400 to 1400 nm, with a sharp peak intensity at about 1270 nm was observed. Also, the broadband optical emission peak at 450 nm was observed [8,9]. The optical intensity distribution is approximately inversely proportional to the cube of the wavelength ($1/\lambda^3$) in the range from 700 to 1400 nm. The optical distribution in the wavelength range from 700 to 1400 nm is thought to be due to Cerenkov radiation induced by gamma-rays [10]. The relation of reactor power and optical intensity of 1270 nm peak is shown in Fig. 6. The peak value is directly proportional to the reactor power.

During heavy neutron irradiation, the absorption of both radiation-resistant optical fibers were quite low in the wavelength range from 750 to 1500 nm. The optical signal in the wavelength range 750 to 1400 nm is not affected by the absorption of optical fibers. The result demonstrates the possibility of using the radiation-resistant optical fibers as a new optical diagnostics for

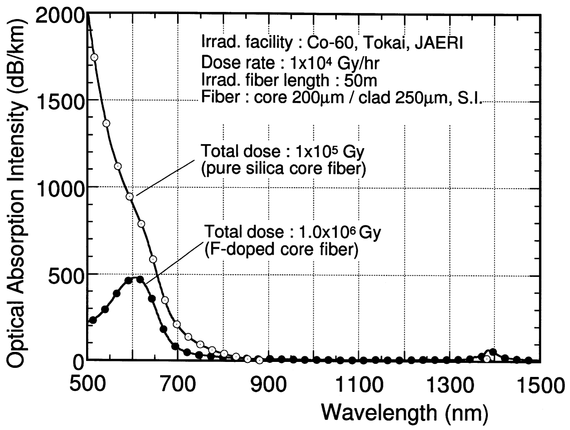


Fig. 4. Observed optical absorption spectra of F-doped core fiber and pure-silica core fiber by medium dose gamma-ray irradiation.

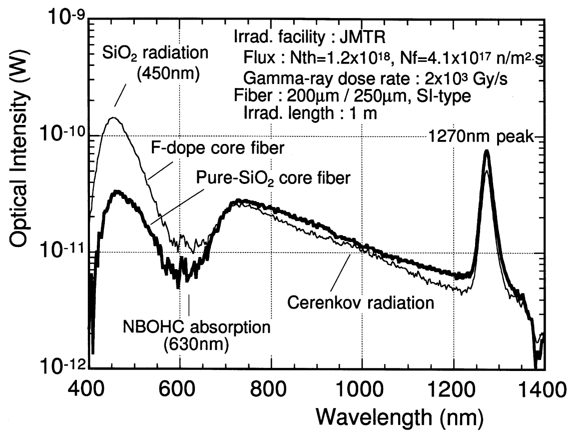


Fig. 5. Observed fluorescence of F-doped core fiber and pure-silica core fiber under fission neutron irradiation.

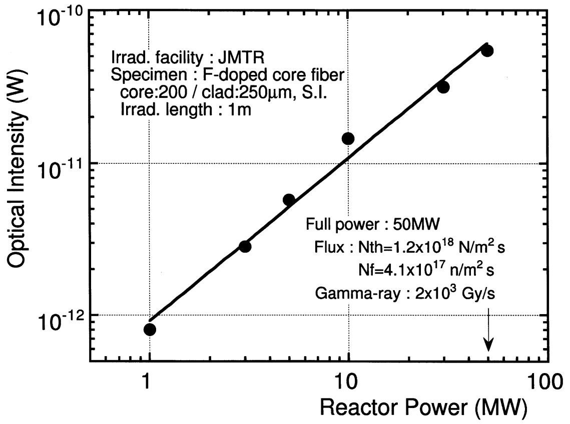


Fig. 6. Relation between reactor power and optical intensity of 1270 nm peak.

fusion reactors e.g. infrared thermometry, gamma-ray thermometry, optical spectrometry.

## 4. Conclusion

Two types of $SiO_2$ based radiation-resistant optical fibers, pure-$SiO_2$ core and Fluorine-doped core were fabricated and their dynamic optical phenomena was examined in the JMTR.

As a result, the following conclusions can be drawn. The absorption induced by heavy neutrons is concentrated in the UV to visible wavelength region. Large and permanent absorption at wavelengths of less than 700 nm was observed. By contrast, the increase in absorption of both fibers was quite low in the wavelength range from 700 to 1500 nm. The radiation-resistant optical fibers appeared to have good radiation-resistance and survived fast neutron irradiation up to about $2 \times 10^{24}$ n/m$^2$, concurrent with gamma-ray doses of $5 \times 10^9$ Gy. The result of absorption measurements showed that effects of the irradiation associated with heavy neutron is different from effects of the ionizing irradiation.

During heavy neutron irradiation, the fluorescence from the optical fiber itself ranging from 400 to 1400 nm with a sharp peak intensity at 1270 nm was observed. The peak value of 1270 nm is directly proportional to the reactor power. The fluorescence signal in the wavelength range 750–1400 nm is not affected by the absorption of optical fibers.

These results demonstrate the possibility of using the radiation-resistant optical fibers as a new optical diagnostics for the fusion reactor.

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